Finite Element Analysis and Design Evaluation of Castellated Beams Fabricated through Rapid Metal Development: A Comparative Study of Sinusoidal, Circular and Hexagonal Web Openings

Suraj Potdar[1], Girish Joshi[2]

[1]PG Student, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *omrajnalage11[at]gmail.com*

[2]Professor, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *girish.joshi[at]raisoni.net*

Abstract: ***Castellated beams are increasingly adopted in long-span steel structures because web perforation permits depth expansion without a corresponding increase in self-weight. However, perforations modify shear flow, induce Vierendeel action and concentrate stresses near web-posts; therefore, refined numerical assessment is needed before design adoption. This paper converts a dissertation-stage study on castellated beams and Rapid Metal Development (RMD) into a journal-style research article. A 6 m simply supported steel beam was modelled in ANSYS and compared for three opening geometries: sinusoidal, circular/cellular and hexagonal. The analysis considered total deformation, equivalent von-Mises stress, normal elastic strain and equivalent elastic strain. The sinusoidal beam recorded a maximum deformation of 4.2418 mm and equivalent stress of 3.3629 MPa, compared with 4.30 mm and 3.50 MPa for circular openings and 5.249 mm and 5.121 MPa for hexagonal openings. Relative to the hexagonal beam, the sinusoidal configuration reduced deformation by 19.19% and equivalent stress by 34.33%. The results indicate that smooth opening geometry can reduce stress concentration and improve serviceability response. The study also demonstrates how RMD-oriented fabrication methods can improve dimensional tolerance, cutting consistency and weld quality, making castellated beams more suitable for industrialized steel construction.***

Keywords: castellated beam; cellular beam; sinusoidal opening; hexagonal opening; Rapid Metal Development; ANSYS; finite element analysis; web opening; Vierendeel action; steel structures

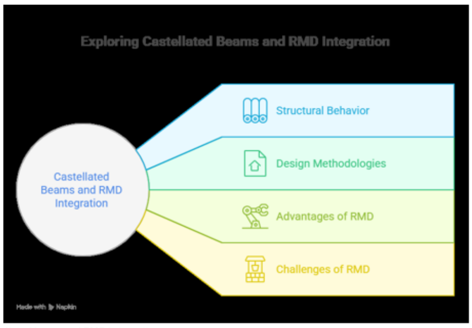
1. Introduction

Modern steel construction increasingly demands long spans, reduced self-weight, fast erection and integration of building services within structural depth. Castellated beams respond to these requirements by cutting the web of a rolled steel I-section in a predetermined pattern, shifting the two halves and welding them to form a deeper member. This process increases overall depth and flexural stiffness without increasing steel tonnage, making the member attractive for pre-engineered buildings, industrial floors, commercial structures and service-integrated floors.

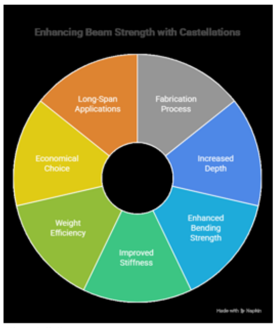
The structural gain obtained from increased depth is accompanied by additional limit states. Web openings interrupt the shear path, introduce Vierendeel bending around openings, generate local stress concentrations and may trigger web-post buckling or lateral-torsional buckling. Consequently, reliable assessment of castellated beams requires detailed numerical or experimental study in addition to conventional beam design checks. AISC Design Guide 31 specifically highlights that castellated and cellular beams require unique design considerations due to repeated web openings [7].

Rapid Metal Development (RMD), as used in the present study, refers to a digital and automated fabrication approach that integrates CNC cutting, controlled welding, jig-based assembly and dimensional inspection. RMD is not treated as a separate material system; rather, it is considered as a fabrication-quality route capable of improving repeatability, accuracy and weld consistency. Recent welding research also confirms the importance of optimizing RMD/FCAW process variables for controlling weld geometry and heat-affected response [9].

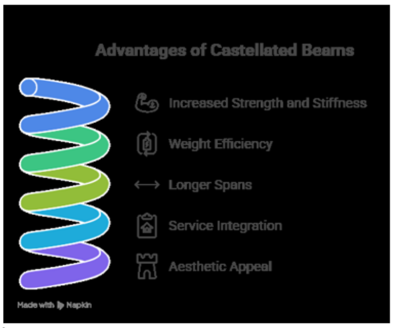
Conceptual and methodology visuals from source report



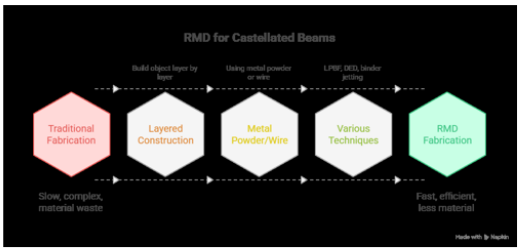
Castellated beam and RMD integration



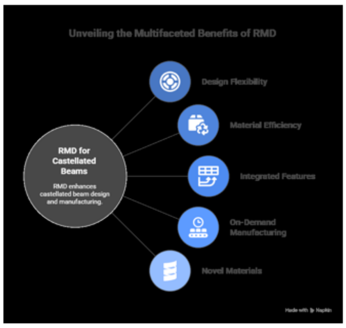
Strength enhancement with castellation



Advantages of castellated beams

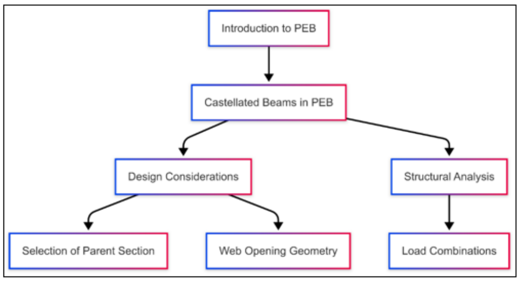


RMD workflow

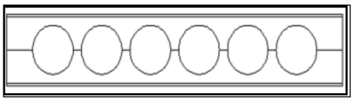


Benefits of RMD

RMD challenges and mitigation



Proposed methodology



Cellular/circular castellated beam

Figure 1: Conceptual, fabrication and methodology visuals extracted from the source report

2. Literature Review and Research Gap

Research on beams with web openings shows that opening area, spacing, web-post slenderness and opening shape strongly influence stiffness, ultimate load and failure mode. Morkhade and Gupta experimentally studied steel beams with web openings and reported reduction in stiffness and ultimate load when the opening area increased, emphasizing the need for geometric optimization [1].

Frans et al. developed a finite element model for hexagonal castellated beams under monotonic loading and found that opening angle and spacing significantly influence yield load, deflection and von-Mises stress response; the reported numerical-experimental difference was within an acceptable range for structural modelling [3]. Pachpor et al. presented design and verification procedures for cellular beams, demonstrating the relevance of plastic and serviceability checks for beams with circular openings [4].

More recent research has extended castellated beam investigation to advanced opening patterns and cyclic response. Naji and Al-Shamaa examined innovative double and zigzag castellated patterns and reported that double-castellated arrangements can improve load carrying capacity when geometry is optimized [2]. Tanady and Suryoatmono numerically examined cyclic behaviour and observed that stress concentration around openings can reduce cyclic performance compared with wide-flange beams [5]. Kaveh and Ghafari further showed that composite action and semi-rigid connection assumptions influence optimum castellated beam design [6].

The reviewed literature confirms that castellated beams are efficient but sensitive to opening geometry and fabrication precision. The identified gap is the limited integrated evaluation of (i) sinusoidal, circular and hexagonal openings under a common finite element framework and (ii) RMD-based fabrication logic as a means of improving dimensional consistency and construction productivity.

A. Research Gap

- Most available studies focus on individual opening shapes; fewer studies compare sinusoidal, circular and hexagonal openings under identical modelling assumptions.
- Conventional design checks often simplify local web-post behaviour and do not explicitly address fabrication-induced geometric imperfections.
- Limited studies integrate castellated beam finite element response with an automated fabrication framework such as RMD.
- There is a need for design-oriented performance indices that connect numerical response, geometry selection and constructability.

3. Materials and Methodology

The methodology adopted in this manuscript follows a research-article format derived from the uploaded dissertation report. The workflow includes literature consolidation, definition of beam geometry, material assignment, RMD-oriented fabrication description, finite element modelling, load application, result extraction and comparative interpretation.

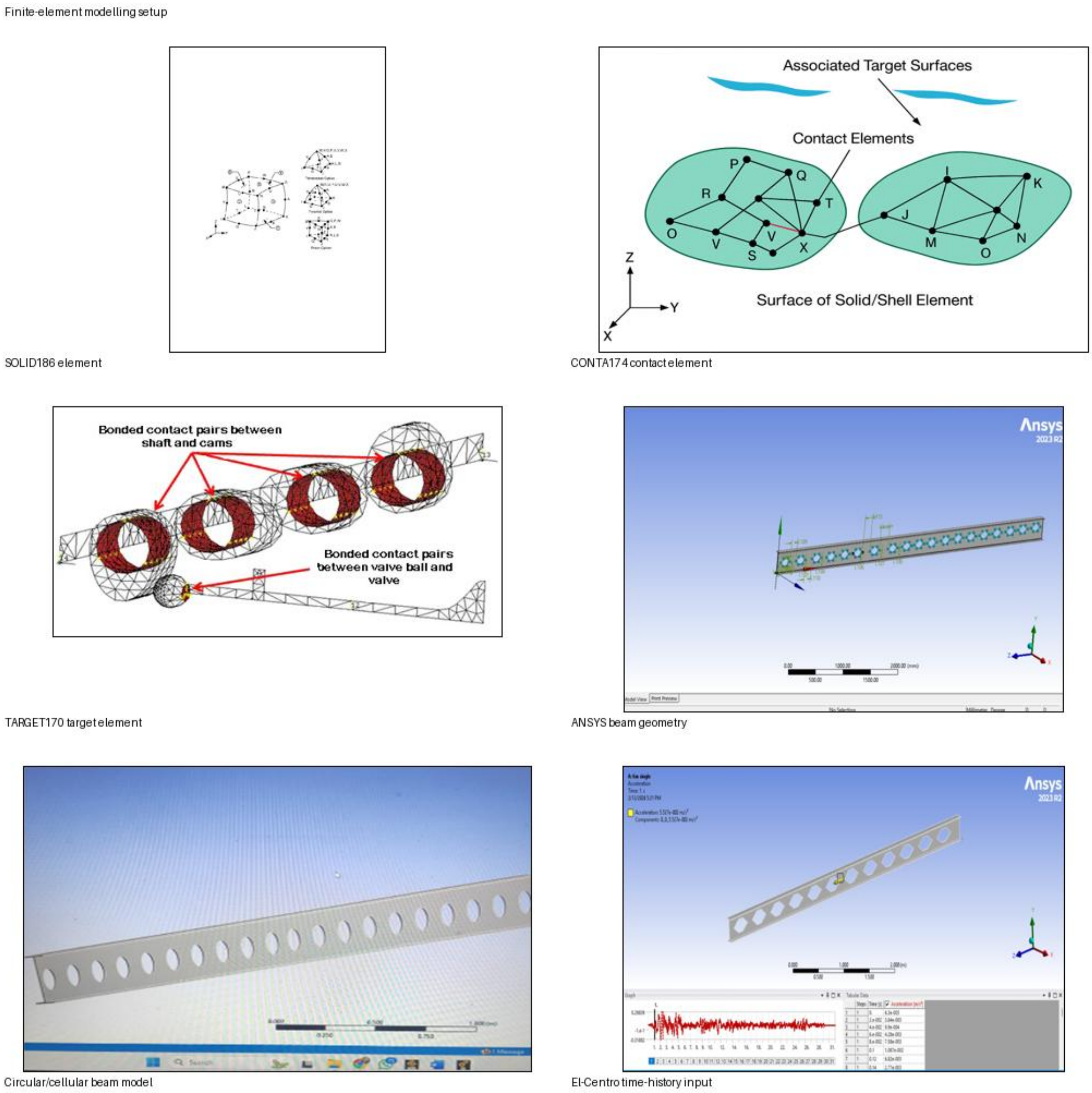


Figure 2: Finite element modelling setup, contact elements and beam models used for the numerical study.

B. Material Properties and Beam Configuration

Table 1: Structural steel material properties adopted in the study

Property	Symbol	Value	Unit
Young modulus	E	2.0 x 10^5	MPa
Poisson ratio	nu	0.3	-
Density	rho	7850	kg/m3
Yield strength	fy	250-350	MPa
Ultimate strength	fu	410-490	MPa
Shear modulus	G	7.69 x 10^4	MPa
Thermal expansion	alpha	1.2 x 10^-5	/deg C

Table 2: Numerical model and design configuration summary.

Item	Description
Parent sections	ISMB 150, ISMB 125 and ISMB 100 were identified as candidate sections in the design documentation.
Case-study section	A simply supported 6 m beam was used for ANSYS response comparison.
Opening geometries	Sinusoidal, circular/cellular and hexagonal web openings.
Boundary condition	Simply supported beam subjected to dead load and live load according to relevant IS provisions.
Output parameters	Total deformation, equivalent stress, normal elastic strain and equivalent elastic strain.

C. RMD-Oriented Fabrication Framework

The RMD framework adopted for castellated beams comprises digital model generation, CNC cutting of web openings, alignment of separated halves, tack welding, automated or semi-automated welding, dimensional inspection, surface treatment and site erection. For castellated beams, fabrication accuracy is especially important because small deviations in opening size, web-post width or weld continuity alter local stress flow. Therefore, automated fabrication is considered an enabling step rather than merely a production shortcut.

- CNC cutting improves repeatability of sinusoidal and cellular patterns.
- Jigs and fixtures help maintain longitudinal alignment after web separation and shifting.
- Robotic or controlled welding improves weld uniformity and reduces defects at rejoined web points.
- Digital inspection supports quality assurance before erection and reduces site rework.

4. Case Study and Finite Element Modelling

The practical case study used in the source report refers to the Amanora Crown Tower, Hadapsar, Pune. A slab/beam system with a simply supported 12 m ISMB 500 layout at the 29th floor level was documented for contextual reference. The numerical comparison in this paper focuses on a 6 m castellated beam analysed in ANSYS for different web opening geometries.

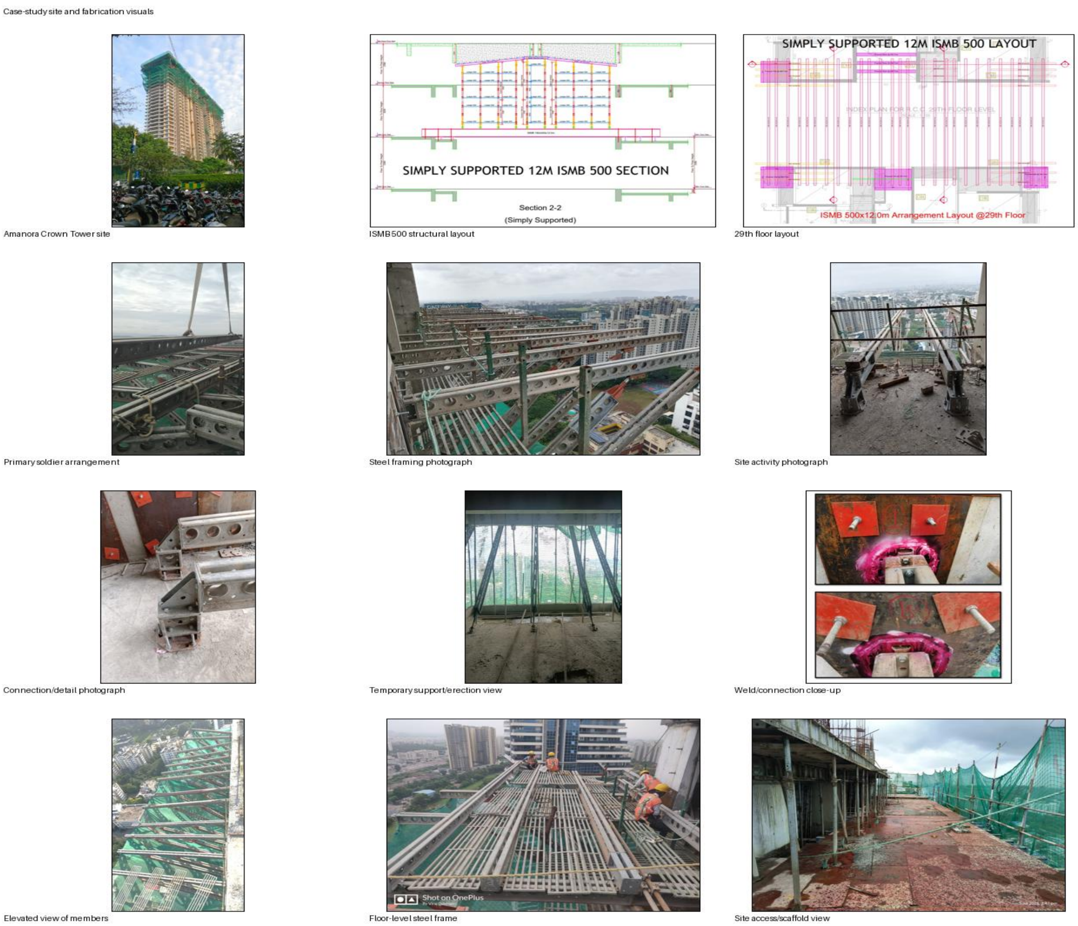


Figure 3: Case-study site, structural layout and construction-stage visuals included from the source report

The finite element model uses higher-order solid elements for steel behaviour and contact/target definitions where interaction or interface effects are required. Mesh refinement around openings is essential because maximum stress and strain develop near hole edges and web-post regions. For interpretation, all response values are presented in consistent units: deformation in mm, equivalent stress in MPa and strain as dimensionless strain.

5. Results and Discussion

The comparative numerical results show that the opening shape has a measurable influence on serviceability and stress response. The sinusoidal opening recorded the lowest deformation and stress, while the hexagonal opening developed the largest values. This trend is consistent with the mechanics of stress concentration: sharp corners in hexagonal openings disturb stress flow more severely than smooth sinusoidal or circular boundaries.

Table 3: Comparative maximum response of castellated beams with different opening geometries

Response parameter	Sinusoidal opening	Circular opening	Hexagonal opening
Total deformation	4.2418 mm	4.30 mm	5.249 mm
Equivalent von-Mises stress	3.3629 MPa	3.50 MPa	5.121 MPa
Normal elastic strain	5.0914 x 10^-6	5.20 x 10^-6	5.30 x 10^-6
Equivalent elastic strain	1.6824 x 10^-5	1.70 x 10^-5	1.75 x 10^-5

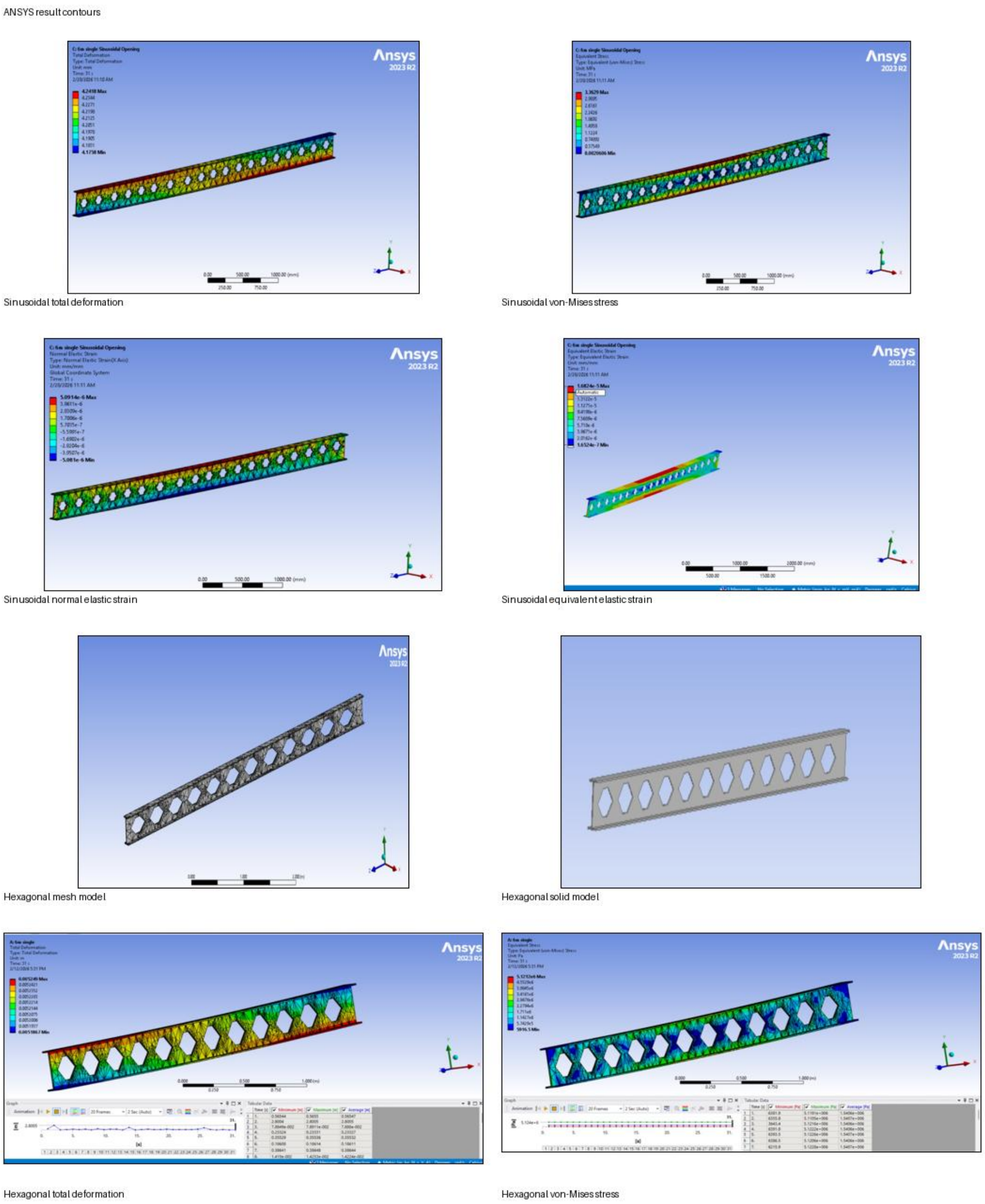


Figure 4: ANSYS deformation, stress, strain, mesh and model contour results from the source report

D. Graphical Comparison of Response Parameters

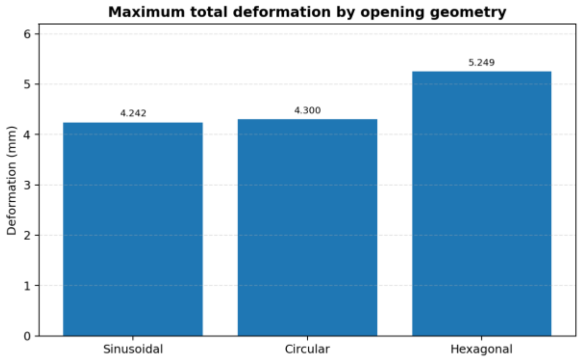


Figure 5: Maximum total deformation comparison for different opening geometries

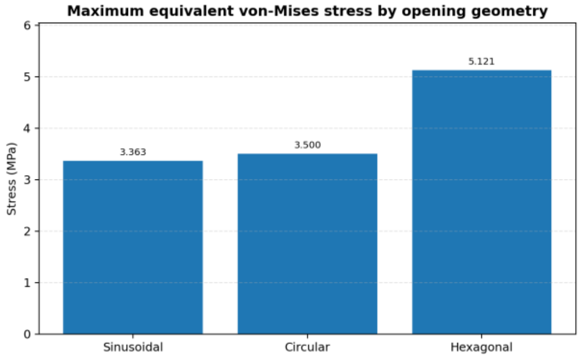


Figure 6: Maximum equivalent von-Mises stress comparison for different opening geometries

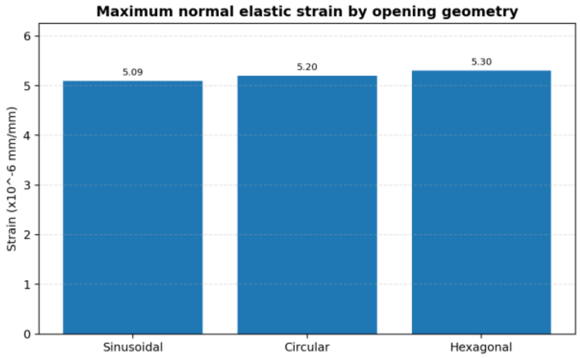


Figure 7: Maximum normal elastic strain comparison for different opening geometries

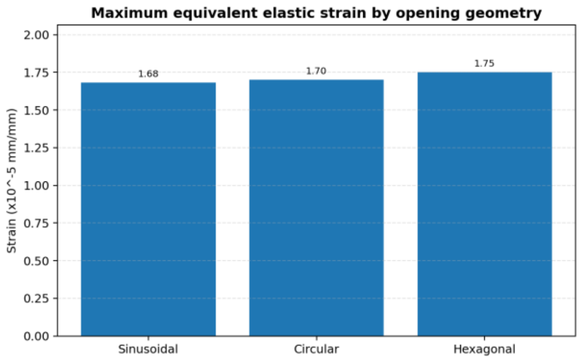


Figure 8: Maximum equivalent elastic strain comparison for different opening geometries

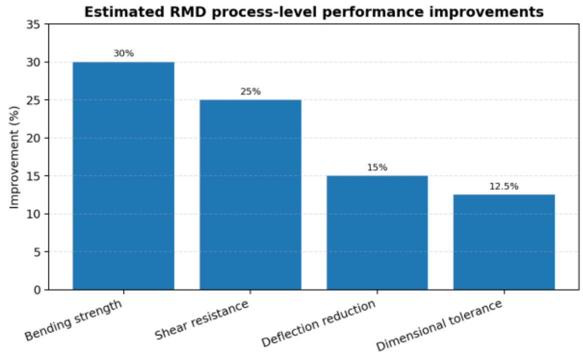


Figure 9: Estimated RMD process-level performance improvements adopted from the study interpretation

E. Derived Performance Indicators

Table 4: Derived performance indicators based on the numerical result dataset.

Indicator	Value
Deformation reduction of sinusoidal beam relative to hexagonal beam	19.19%
Equivalent stress reduction of sinusoidal beam relative to hexagonal beam	34.33%
Normal strain reduction of sinusoidal beam relative to hexagonal beam	3.94%
Equivalent strain reduction of sinusoidal beam relative to hexagonal beam	3.86%
Deformation reduction of sinusoidal beam relative to circular beam	1.35%
Equivalent stress reduction of sinusoidal beam relative to circular beam	3.92%

The derived indicators show that the principal advantage of sinusoidal openings is stress reduction. The difference between sinusoidal and circular openings is modest, but the difference between sinusoidal and hexagonal openings is substantial because the hexagonal geometry produces corner-induced local concentration. Therefore, where fabrication facilities allow smooth-cut geometry, sinusoidal or cellular openings should be preferred in serviceability-sensitive long-span applications.

6. Principal Findings

- Opening shape controls the local stress field: smoother openings reduce abrupt discontinuities in the web and therefore reduce maximum equivalent stress.
- The sinusoidal castellated beam showed the best overall response in the adopted dataset, with 4.2418 mm maximum total deformation and 3.3629 MPa maximum equivalent stress.
- Hexagonal openings developed the highest deformation and stress because sharp corners promote stress concentration and Vierendeel action around the opening edge.
- Circular/cellular openings produced intermediate behaviour, supporting their frequent use in service-integrated structural floors where smooth stress flow and aesthetics are required.
- RMD-based fabrication is beneficial because opening shape accuracy, weld continuity and controlled assembly strongly influence finite element response and real structural performance.

- The generated graphs confirm that geometry optimization must be paired with fabrication control; analytical optimization alone is insufficient if cutting or welding tolerances are poor.

7. Conclusion

This research article investigated the finite element response and design relevance of castellated beams fabricated through an RMD-oriented workflow. The analysis compared sinusoidal, circular and hexagonal web openings for a simply supported steel beam, using total deformation, equivalent stress and elastic strain as performance measures.

The results indicate that the sinusoidal opening is structurally the most efficient among the three compared configurations. It reduced maximum deformation by 19.19% and equivalent stress by 34.33% relative to the hexagonal opening. Circular openings also performed better than hexagonal openings, but slightly below the sinusoidal geometry in the adopted dataset. The study confirms that castellated beams are not governed only by increased flexural depth; local opening geometry, web-post behaviour, Vierendeel bending, weld quality and fabrication tolerance jointly determine actual performance. Therefore, design of castellated beams should combine code-based checks, finite element verification and fabrication-aware quality control.

RMD techniques such as CNC cutting, robotic welding, digital layout extraction and controlled inspection can improve the reliability of castellated beam fabrication. This is especially important for sinusoidal and cellular openings, where geometric precision directly affects stress distribution and structural repeatability.

8. Recommendations and Future Scope

- Experimental testing should be conducted to validate the numerical response of sinusoidal, circular and hexagonal openings under static, fatigue and seismic/cyclic loading.
- Future finite element models should include geometric imperfections, weld residual stresses and nonlinear material behaviour to capture ultimate failure mechanisms.
- Optimization studies may vary opening depth, pitch, web-post width, fillet radius and end-hole filling to develop design charts for Indian steel sections.
- Composite action between castellated beams and concrete slabs should be investigated for PEB and multi-storey floor systems.
- Life-cycle assessment should be performed to quantify the sustainability benefit of material saving, reduced fabrication waste and faster erection through RMD.

9. Limitations

The work is primarily numerical and uses maximum response values available from the dissertation-stage output. Circular opening values were interpreted as approximate where the source report provided rounded values. The RMD improvement chart represents a process-level interpretation from the study conclusion and should be experimentally validated before direct industrial adoption. The study is limited to steel castellated beams and does not fully quantify fatigue, fire, fracture, residual stress or long-term durability.

Declarations

Data availability: The result dataset used in the graphs is reproduced from the dissertation report and normalized into consistent units for manuscript preparation.

Conflict of interest: The authors declare no conflict of interest for academic manuscript preparation.

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